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Self-arresting fatigue cracks at notches in nodular cast iron

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Abstract

The durability assessment of a mechanical component is frequently based on the elastically calculated stress cycle at the critical point, thus neglecting the influence of local plasticity or a stress gradient. Since this tends to yield over-conservative predictions of the fatigue strength of the component, several mainly empirical methods have been introduced to account for 'non-local' effects. Formally well suited for a durability assessment based on FEA are the methods of the critical distance, the normalized stress gradient and the highly stressed material volume.

A more fundamental approach takes into account the growth of a fatigue crack from the critical point of the component. Thus, in a classical paper, Frost demonstrated that the fatigue strength of notched components could be explained by the occurrence of non-propagating or 'self-arresting' cracks. The present work considers self-arresting cracks in nodular cast iron EN-GJS-400-18-LT, frequently used in wind-turbine components. A fracture mechanics model is proposed in this work to predict fatigue failure in notched components. To validate the model, representative notched specimens have been subjected to fatigue testing. The agreement between testing and modelling results supports the short-fatigue-crack-growth model proposed.

Keywords: Short cracks; non-propagatin cracks; self-arresting cracks; notches; cast iron

1. Introduction

Increasing interest in energy generated by wind turbines brings new challenges to the designers that search for making the best use of the materials. The constant increment in the power and thus in the size of these turbines leads to an increasing use of ductile cast iron [1]. One of the materials most used in the wind turbine construction is the ductile cast iron EN-GJS-400-18-LT. Geometric discontinuities within the components such as holes, fillets, threads, grooves, cast defects, etc, cause a high stress concentration. These stress raisers may be treated as notches. In addition their stress raiser effects are localized near to the notch tip [2]. The impossibility of designing components avoiding geometric discontinuities leads to improve or create methods to predict accurately the fatigue limit of components containing notches. Usually the life of a mechanical component is predicted taking into account only σ_{max}, the maximum stress at the critical point $\sigma_{max}=K_t \cdot S_a$, where K_t is the elastic stress concentration factor and S_a is the nominal stress amplitude applied. This approach does not consider other effects such as the stress gradient or local plasticity at the notch root. Experimental evidence shows that sharp notches are less severe in fatigue than

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indicated by the maximum stress at the notch root [3]. This leads to very conservative predictions. Therefore several methods have been introduced to try to improve life estimation. The empirical notch sensitivity factor q is a useful concept to deal with notch effects. Peterson [4] and Neuber [5] used the notch sensitivity concept to develop two different equations to compute the well known fatigue notch factor, K_f [2]. New methods have been developed recently, the theory of critical distance by David Taylor [6], the normalized stress gradient [7], the method of highly-stressed volume [8], the weakest-link theory [9-10], amongst others.

As is well known, when a mechanical component containing notches is stressed under cyclic loading small cracks appear at the notch root due to the high local stress [11]. These cracks could propagate until causing the final failure or they may be arrested, and then the cracks do not go on propagating (self-arresting cracks) [11-13]. Predicting if a small fatigue crack started at a notch root is going to propagate until causing the final failure, is still a challenge. This means that life prediction of components with notches that act as high stress risers is still at least in discussion. A better understanding of the crack initiation and propagation processes from high stress risers is necessary to improve the existing life predictions. This implies a better understanding of the behavior of small cracks.

In this research, a study of the effect of notches in the fatigue limit of cast iron EN-GJS-400-18-LT is performed. A fracture mechanics model is applied to predict fatigue failure in notched components with different notch radii. Self arresting cracks are also predicted. Eventually a comparison of the fracture mechanics model and experimental results is performed.

Nomenclature

a	actual crack length
a_0	characteristic crack length
w	half of the gross section width
C	Paris law constant
d	notch depth
E	modulus of elasticity
F	arbitrary correction factor
F_w	free surface correction factor
F_n	notch correction factor that takes into account the notch stress field
K_f	fatigue notch factor
K_t	elastic stress concentration factor
K_{tg}	elastic stress concentration factor referred to the gross-section
m	Paris law exponent
P_f	Probability of failure
q	notch sensitivity factor
R	stress ration
R_m	ultimate tensile strength
$R_{0.2}$	0.2% proof strength
S_a	net/nominal stress amplitude
σ_A	median fatigue limit, P_f=50%
t	specimen thickness

Z	reduction of area
σ_{max}	maximum stress at the notch root
ΔK	stress intensity range
ΔK_{eq}	equivalent stress intensity factor range
ΔK_{th}	threshold stress intensity range
ΔS_{th}	maximum stress range that is not able to propagate a crack of length a
ΔS	gross nominal stress range
$\Delta\sigma$	local stress range at the notch root

2. Experiments

2.1. Material

The material analysed in this research is a nodular ductile cast iron, EN-GJS-400-18-LT [14]. The material properties are in Table 1 and chemical composition is in Table 2. The chemical composition was measured.

Table 1. Mechanical properties, EN-GJS-400-18-LT.

R_m (MPa)	$R_{0.2}$ (MPa)	Z (%)	E (GPa)	σ_A (MPa)
400	250	18	167	195

Table 2. Chemical composition wt.%, balance Fe.

C	Si	Mn	P	S	Ni	Mg
3.61	2.18	0.23	0.014	0.009	0.088	0.041

2.2. Fatigue tests

Fatigue tests were carried out on notched specimens to determine the presence of self-arresting cracks at the notch tip. The notched specimens were tested under reversed loading (R = -1). Self-arresting cracks were detected and measured in the notched specimens after two million cycles. Specimens were made of EN-GJS-400-18-LT and the geometry is presented in Fig. 1. A fatigue machine (Instron servo-hydraulic, capacity 100 kN) was used to test the specimens. The specimens were machined with different notch radii but with the same notch depth d = 5.1 mm. Thus different values of K_t and stress gradients are introduced in the specimens. The same thickness was used for all the specimens t = 7.7 mm. The different notch radii and stress concentration factors are specified in Table 3. An equation proposed in Dubbel engineering hand book [15] is used in this work to calculate the different values of K_t. An electro erosion machine was used to make the different notch radii. Three specimens were machined for each notch radius, and they were tested at different stress ranges. A travelling microscope was used to inspect the surface at the notch root across the specimen thickness. After two millions of cycles the run out specimens were submerged in liquid nitrogen, and then monotonically loaded until fracture. Then the broken specimens were analysed in the optical microscope looking for self-arrested cracks. Self-arrested cracks were localised at the notch tip and measured.

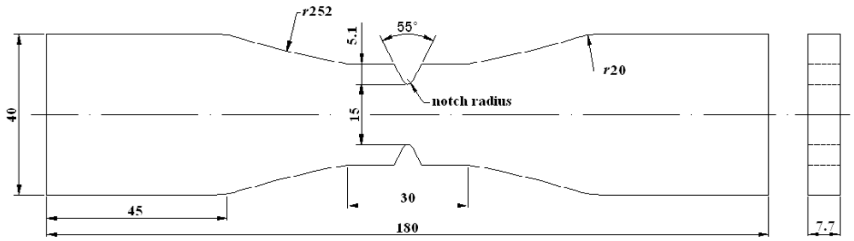

Fig. 1. Notched specimen geometry (all the dimensions in mm).

Table 3. Notch radii and stress concentration factors for the different specimens.

Specimen type	Notch radius (mm)	K_t
A	0.19	7.5
B	0.46	5.0
C	0.59	4.5

3. Self-arresting cracks

3.1. Short crack modelling

As is well known, Paris et al. [16] proved that the fatigue crack growth behaviour, for long cracks, may be described by the relationship between fatigue crack growth rate da/dN and the stress intensity range ΔK:

$$\frac{da}{dN} = C\left(\Delta K\right)^m \tag{1}$$

C and m are material parameters. Klesnil and Lukás [17] extended the above equation into the near-threshold region:

$$\frac{da}{dN} = C(\Delta K^m - \Delta K_{th}^m) \tag{2}$$

ΔK_{th} is the threshold stress intensity range. El Haddad et al. [12] defined an equivalent stress intensity factor range ΔK_{eq}, which is valid for short cracks, as:

$$\Delta K_{eq} = \Delta S\sqrt{\pi\left(a+a_0\right)} \tag{3}$$

ΔS is the gross nominal stress range, a is the actual crack length and a_0 is the characteristic crack length, and it represents the transition between short ($a < a_0$) and long cracks ($a > a_0$). a_0 is defined as:

$$a_0 = \frac{1}{\pi}\left[\frac{\Delta K_{th}}{\Delta\sigma_A}\right]^2 \tag{4}$$

$\Delta\sigma_A$ is the material fatigue limit. Eq. (3) and Eq. (4) may be generalized using an arbitrary correction factor F, as proposed by Härkegård [18], i.e.:

$$\Delta K_{eq} = F\Delta S\sqrt{\pi\left(a+a_0\right)} \tag{5}$$

$$a_0 = \frac{1}{\pi}\left[\frac{\Delta K_{th}}{F\Delta\sigma_A}\right]^2 \tag{6}$$

This is correct for a smooth specimen, but for a crack starting at the notch root this would be true only if ΔS is the stress range at the notch root $\Delta\sigma$. Therefore if $\Delta K_{eq} \to \Delta K_{th}$ and $a \to 0$, then $\Delta\sigma = K_{tg}\cdot\Delta S = \Delta\sigma_A$, where K_{tg} is the elastic stress concentration factor referred to the gross-section. The correction factor F may be expressed in terms of two different factors i.e. $F = F_w\cdot F_n$ [19], where F_w is the free surface correction and F_n is a notch correction factor that takes into account the notch stress field. As $F_n = K_{tg}$ when $a \to 0$, then Eq. (5) and Eq (6) may be written as:

$$\Delta K_{eq} = F_w \cdot F_n \cdot \Delta S\sqrt{\pi\left(a+a_0\right)} \tag{7}$$

$$a_0 = \frac{1}{\pi}\left[\frac{\Delta K_{th}}{1.12\ \Delta\sigma_A}\right]^2 \tag{8}$$

The maximum gross nominal stress range that is not able to propagate a crack of length a, ΔS_{th}, may be obtained replacing $\Delta K_{eq} = \Delta K_{th}$ and $\Delta S = \Delta S_{th}$ into Eq. (5), Thus:

$$\Delta S_{th} = \frac{\Delta K_{th}}{F_w F_n\sqrt{\pi\left(a+a_0\right)}} \tag{9}$$

Eq. (9) reproduces the Kitagawa-Takahashi diagram [13] when $F = F_w F_n = 1$. Fig. 2 shows the variation of $\Delta\sigma_{th}/\Delta\sigma_A$ with the normalised crack length a/a_0. $\Delta\sigma_A$ is used to normalise ΔS_{th}, and a_0 to normalise a. As may be seen in Fig. 2, $\Delta S_{th} \to \Delta\sigma_A$ as $a \to 0$ i.e $a \ll a_0$.

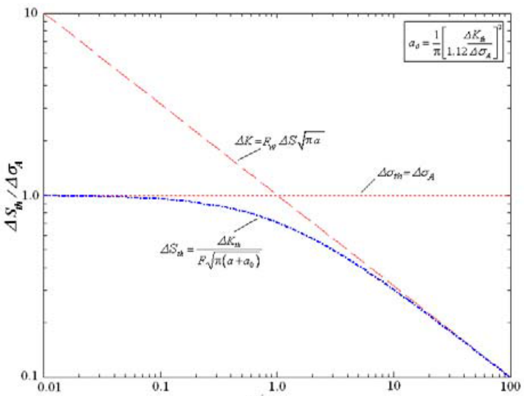

Fig. 2. Kitagawa-Takahashi diagram.

3.2. Failure prediction in notched specimens

Eq. (7) may be able to modelling the behaviour of short fatigue cracks growing from a notch tip, if suitable F_n and F_w are implemented. Härkegård [18], proposed the below expression for F_σ:

$$F_n = \sqrt{1+\frac{d}{a}\left[1-\exp\left(-\frac{a}{a'}\right)\right]} \quad , \tag{10}$$

where:

$$a' = \frac{d}{k_{tg}^2 - 1} \quad . \tag{11}$$

For the geometry presented in Fig 3 (a), Tada [20] proposed a suitable expression for F_w within 0.5% accuracy:

$$F_w = \left(1 + 0.122\cos^4\frac{\pi\cdot\varphi}{2}\right)\sqrt{\frac{2}{\pi\cdot\varphi}\tan\frac{\pi\cdot\varphi}{2}} \tag{12}$$

Where $\varphi = (a + d) / w$ and w is half of the gross section width. Self-arresting cracks may be predicted using Eq. (7) and a fatigue crack growth equation may be written replacing $\Delta K = \Delta K_{eq}$. in Eq. (2), i.e:

$$\frac{da}{dN} = C(\Delta K_{eq}^m - \Delta K_{th}^m) \tag{13}$$

Eq. (13) predicts a finite crack growth rate even for a crack of vanishing depth. Eq. (7) may be used to predict fatigue failure in notched specimens. Fig 3(b) shows that Eq. (7) is able to predict failure accurately in components made of nodular cast iron EN-GJS-400-18-LT [14]. A ΔK_{th}=14 MPa produces good results, this value is in accordance with the value suggested in [21] for nodular cast irons.

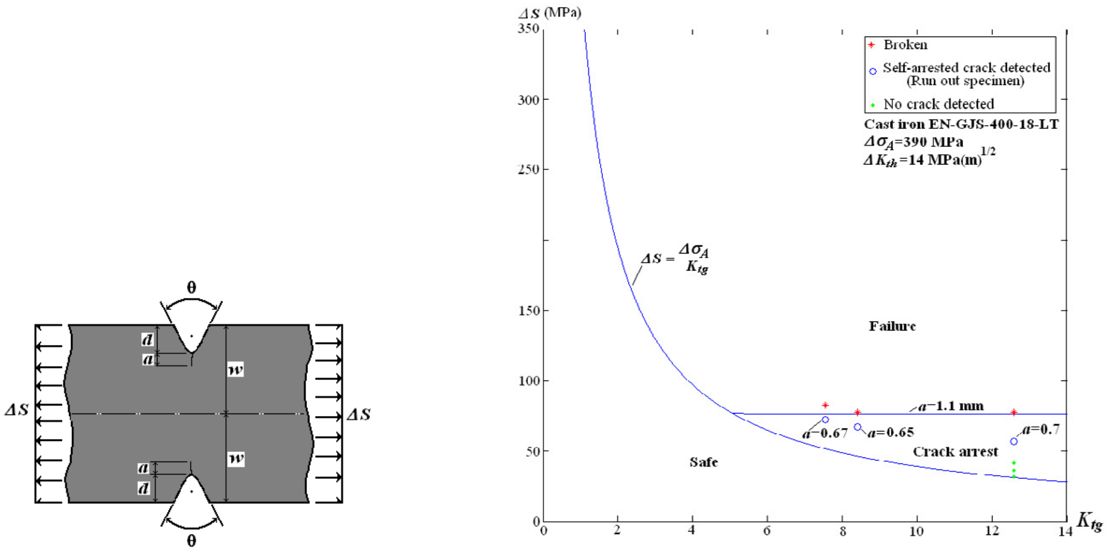

Fig. 3. (a) Double edge notch; (b) Failure predicted by Eq. (7) and experimental data

4. Conclusions

As is seen in Fig. 3(b) fatigue failure may be predicted using a fracture mechanic model without any empirical assumption. Experimental data corroborates the accuracy of the fracture mechanic model. The traditional method that only takes into account σ_{max} to predict fatigue failure (the highest local stress method) underestimates the fatigue life of notched components. In addition self-arresting cracks was observed in the run out specimens, and these cracks seem to explain the difference between the experimental data and the predictions of the highest local stress method. As is seen in Fig. 3(b) the highest stress method is not able to neither predict fatigue failure nor crack initiation for high stress concentration factors.

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